Power Tower R&D

Performing Organizations: Sandia National Laboratories (SNL)

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FY 2008 Budgets: \$233K (DOE-CSP) \$350K (DOE-Hydrogen)

Objectives

Perform R&D to support development of advanced power tower systems

Accomplishments

- Helped Rocketdyne begin development of their own heliostat
- Performed first-ever test of a heliostat at a distance of 1 mile
- Updated SOLERGY software to better predict annual performance of steam receivers
- Trained power tower developer to use Sandia's design and analysis software
- Performed initial tests of a solid-particle receiver

Future Directions

- Work with industry to develop and test components to be used in commercial projects
- · Develop advanced analysis tools and portable test equipment
- Perform proof-of-concept test of solid-particle receiver

1. Introduction

Due to the resurgent interest in solar power towers by US industry (Solar Reserve, eSolar, and BrightSource), DOE funded Sandia to work with industry to support near-term commercial projects. R&D to support the development of electricity-generating power towers had been suspended by DOE for many years prior to the resumption of the work described here.

Since 2004 DOE has funded Sandia to work with other research organizations to develop solar methods of producing hydrogen. In 2008 Sandia tested a leading power-tower approach, known as the solid-particle receiver.

2. Technical Approach

Sandia met with the US power tower developers to determine critical technology needs. Tasks that could be performed within the limits of the DOE budget allocation were defined. The tasks defined were A) help Rocketdyne get started on developing their own heliostat, B) perform 1-mile

heliostat test, C) update SOLERY to better simulate steam power towers (supports eSolar and Brightsource), and D) train Rocketdyne to use Sandia's power-tower software and demonstrate it to eSolar.

In support of DOE's solar-hydrogen program, Sandia built and tested a 2 MWt solid-particle receiver prototype. The purpose of this initial relatively low-budget test was to validate analytical models, demonstrate flow stability, and to gain some practical experience that will help us define the characteristics of a future proof-of-concept test.

3. Results and Accomplishments

3.1 Help Rocketdyne begin heliostat development

Solar Reserve and Rocketdyne are commercializing Solar-Two-type power tower technology. Rocketdyne has a long history in power tower development and were responsible for the construction of the Solar One steam receiver and Solar Two salt receiver. In 2008

Rocketdyne made a business decision to expand their scope of supply to include heliostats.

Sandia performed tech transfer activities with the Rocketdyne heliostat team. We met with them on several occasions and made sure they were aware of the main conclusions of the heliostat R&D conducted over the years. Sandia also sent Rocketdyne several mirror facets and loaned them 2 azimuth drives to help them construct initial prototypes.

Rocketdyne's initial heliostat prototype is nearing completion and should be operating by the end of March, 2008.

3.2 Perform 1-mile heliostat test

The Solar Reserve tower plant is capable of producing 100 MWe or more. The area of the heliostat field within their commercial plant is more than 10 times larger than was demonstrated at Solar Two. For example, at Solar Two the distance from the tower to the furthest heliostat was 0.25 mile; in the commercial plant this distance is 1 mile. To reduce the scale-up risk, Sandia analyzed the performance of a heliostat at the 1-mile distance.

The 1-mile test was performed at Sandia by aiming a 100 m^2 heliostat at two existing 140-foot-tall towers located 0.97 miles to the Southeast. Test data indicated that the spot size was 20 meters in diameter. This spot size agrees well with a prediction by Sandia's DELSOL computer code.

See the accompanying vugraph presentation for technical data and more information.

3.3 Update SOLERGY to better predict the performance of steam receivers

Sandia's SOLERGY code is used to simulate the operation and power output of a user-defined solar central receiver power plant for a time period of up to one year. SOLERGY utilizes recorded or simulated weather data (15-minute intervals) and plant performance models to calculate the power flowing through each part of the solar plant. A plant control subroutine monitors these powers and determines when to operate the various plant subsystems.

Code predictions have been compared with data from the Solar One steam receiver plant and the

Solar Two salt receiver plant. The code does a better job of simulating a molten salt plant because the receiver and turbine-generator are able to operate during partly cloudy weather and use of 15-minute average direct-normal insolation (DNI) data is an adequate representation of insolation transients. Steam receivers, on the other hand, typically trip offline within a few minutes during partly cloudy conditions due to rapid degradation of steam temperature and pressure. Receiver trip leads to a turbine trip because there is no buffer storage between the receiver and turbine. During our validation effort conducted in the late 1980's we found that use of 15-minute average DNI data caused SOLERGY to overpredict Solar One's actual performance by 16%. We showed that use of 3minute data gave a much better estimate, but 3minute data is not generally available for many sites.

Since eSolar and Brightsource are resurrecting water-steam receiver technology, Sandia decided to improve SOLERGY's model of steam receiver plants and revalidate this new model with Solar One data. The new receiver model will automatically trip the receiver when insolation within a given time step is less than XX% of the clear-sky value that is predicted for that time step at a given plant location. We found that a value of 60% allows SOLERGY to achieve a much better prediction of actual Solar One performance. The value for the receivers being developed by eSolar and BrightSource may be different than 60%, but this value can be readily changed.

See the accompanying vugraph presentation for technical data and more information.

3.4 Power Tower software training

Solar Reserve and Rocketdyne commercializing Solar-Two-type power tower technology. They have historically used in-house ray-tracing software to design and analyze the technology. The computational resources of the ray-tracing codes are extensive; this was becoming an impediment to the guick turn-around requirements of their commercial venture. Consequently, Sandia trained them on the use of Sandia's DELSOL and SOLERGY computer codes, which are much less computationally extensive but have nevertheless been shown to accurately predict power tower optical design and performance.

3.5 Solid Particle Receiver Test and Evaluation

Since 2004 Sandia has been investigating solar interfaces appropriate for providing heat input to thermochemical fuel production processes. Many of these processes require thermal energy to be input at a temperature in excess of 800 C. In addition, the ability to provide this heat input around-the-clock is advantageous from an operational perspective and necessitates the use of thermal storage. The solid particle receiver (SPR) is a direct absorption central receiver concept initially conceived in the 1980's. It utilizes a curtain of spherical ceramic particles that serve as both the heat transfer fluid (HTF) and thermal storage media. The principle advantages of the SPR are 1) potentially high receiver efficiency due to direct absorption, 2) operational temperatures in excess of 1000 C, and 3) chemically benign solid HTF and storage media.

The initial SPR development efforts that took place in the 1980's resulted in a wealth of data related to the properties of solid particle HTFs and thermal performance under idealized test conditions. In addition, a computational model was developed based on the particle source in cell (PSICELL) approach that allowed for an estimation of receiver

performance. This model was validated with the experimental data that was available at the time, but which did not include on-sun testing of an open cavity receiver. Since then, additional models have been developed in collaboration with UNLV, NETL using MFIX, and most recently with researchers from DLR in Germany. The desired outcome of these modeling efforts is to both improve our understanding of the complex multiphase transport processes occurring within the receiver and to develop a simulation tool that may be used in the future design of commercial scale SPR systems. A necessary step in achieving this is to provide an appropriate experimental platform and use it to produce the experimental data needed to validate these models and establish confidence in their predictions.

An initial prototype SPR was tested on top of Sandia's 61 m tall central receiver tower located at the National Solar Thermal Test Facility (NSTTF) in Albuquerque, NM. The prototype operated in batch mode with a total particle inventory of roughly 1800 kg. The alumina particles are commercially available from CarboCeramics and are the size of common beach sand. Depending on the flow rate, tests were run from roughly three minutes to just over seven minutes.

Testing was conducted using a single aimpoint in the center of the aperture. The maximum number of heliostats used in a test was 140, enough to deliver 2.5 MW of thermal energy to the receiver. The temperature increase of the particles during on-sun testing ranged from 100 °C to nearly 250 °C for a single pass through the cavity. The receiver efficiency was calculated by dividing the energy gain of the particles by the amount of energy entering the aperture. Fifty-seven percent efficiency was the maximum obtained. Due to budget

limitations, this prototype receiver did not operate at the higher flux levels or temperature required for a commercial device.

One concern prior to testing on-sun was the potential impact on curtain stability of buoyancy driven flow within the cavity. Although the particles are dense and acquire a relatively large amount of momentum as they fall, there is a chance that air currents could be set up within the cavity that would disturb the uniformity of the particle curtain. We did not observe this during testing even though the air within the cavity achieved temperatures in excess of 800 °C, through contact with the hot cavity walls.

A related concern is the impact of ambient wind on the particle flow within the open cavity receiver. In commercial scale systems, the receiver cavity might be located 200 m or more above the ground and exposed to almost constant winds. We measured wind speed at the aperture prior to most tests. The maximum measured wind speed was in excess of 13 m/s, with most tests conducted when winds exceeded 5m/s. In most cases the wind came either directly out of the north or the south and had little effect on the curtain regardless of speed. Winds that were not directly normal to the aperture did produce some instability in the curtain. This observation is consistent with predictions of our computational models.

The on-sun test program provided a foundational data set for the validation of existing and future computational models. The demonstration of a single pass temperature increase in excess of 200 °C at practical particle mass flow rates is an encouraging result, as is the relative stability of the curtain when exposed to wind and buoyant flows. We are, however, reluctant to say that the overall feasibility of the concept has been sufficiently demonstrated. That will involve achieving four primary milestones:

- 1. The demonstration of a particle exit temperature in excess of 900 °C. This is the temperature required to produce hydrogen with sulfuric-acid-cracking cycles. To achieve 900 °C we must optimize the optical design of the receiver. For example, in the current test the average flux on the particle curtain was 400 suns. Our performance models indicate that an 800 sun average will be required to achieve 900 °C given an inlet temperature of 600 °C. Achieving 900 °C may also require recirculation of the particles to increase residence time for a receiver of the size that we're likely to test. In larger systems having a greater drop distance recirculation may not be necessary.
- 2. The demonstration of receiver efficiency in excess of 70% (heat absorbed/power into aperture). This can be achieved by increasing the average flux on the curtain by increasing the incident power (only half of our field was used in these tests) and reducing the unheated length of the curtain. It is also likely that using smaller particles would improve efficiency.

- 3. The development of a rigorous multi-phase analysis of the impact of ambient wind on curtain stability in an open cavity and the demonstration of strategies to mitigate this issue. CFD simulations indicate that a potentially feasible concept is to draw air through small holes in the back wall and reintroduce it into the ceiling structure of the cavity. Sandia is seeking a patent on this concept.
- 4. The demonstration of the physical stability of the particles i.e. that particle attrition due to self abrasion is within acceptable limits for economical plant operation.

Achieving these milestones will require a mix of computational and experimental efforts. We currently plan to proceed with the validation of existing computational models using the data collected in the initial test program and then to design an optimized cavity receiver based on our current test platform and suitable for use at the NSTTF with our entire field, rated at over $4 \ MW_{th}$.

See the accompanying vugraph presentation for technical data and more information.

Energy Engineering, May 2007, Vol. 129, p 179-183.

Siegel, N., G. Kolb, et. al., "Solid Particle Receiver Flow Characterization Studies," *Proceeding of Energy Sustainability 2007*, Long Beach, CA, June 20-27, 2007.

Sandia National Laboratories, "Suction Recirculation Device for Stabilizing the Flows within a Solar-Powered Solid Particle Receiver," Patent Application, SD-10824/S114013, 2009.

6. University and Industry Partners

- Solar Reserve
- Hamilton-Sunstrand Rocketdyne
- eSolar
- University of Nevada Las Vegas.

4. Planned FY 2009 Activities

- Current plans call for Sandia to test up to 3 Rocketdyne prototype heliostats in 2009.
- Sandia will help eSolar model the performance of their steam-type power towers. eSolar and Sandia are establishing a "Work-for-Others" type contract to perform the work
- Modernize Sandia's power tower design and analysis software

5. Major FY 2008 Publications

Siegel, N., and G. Kolb, "Design and On-Sun Testing of a Particle Receiver Prototype," *Proceeding of Energy Sustainability 2008,* Jacksonville, FL, August 10-14, 2008. BEST PAPER AWARD.

Kolb, G., and R. Diver, Screening Analysis of Solar Thermochemical Hydrogen Concepts, SAND2008-1900, March 2008.

Kolb, G., R. Diver, and N. Siegel, "Central-Station Solar Hydrogen Power Plant," *Journal of Solar*